Modeling the Tidal Tails of the Sagittarius Dwarf Galaxy

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Abstract. N-body simulations are used to model the tidal disruption of the Sagittarius (Sgr) dwarf galaxy with constraints set by the positions and velocities of M giants in the Sgr tidal arms recently revealed by the Two Micron All-Sky Survey (2MASS). The simulated Sgr dwarf is placed on a variety of orbits within a Milky Way potential parameterized by variable circular velocities, halo flattenings and radial profiles. Two hundred separate test particle orbits have been used to explore a wide range of model Milky Way potentials and dwarf galaxy characteristics. The family of models is delimited by the data to a relatively narrow allowed range of parameters, and then input into N-body simulations. We present our best-fitting model, and discuss the orbital period, apoGalacticon distance, current space velocity, mass-to-light ratio, and other characteristics of the Sgr dwarf. In addition, we discuss the implications of this model for the flattening of the Galactic halo.

1. Introduction

Since the discovery of the Sgr dwarf by Ibata et al. (1994) many groups (e.g., Johnston, Hernquist, & Bolte 1996, Ibata et al. 1997, Ibata & Lewis 1998, Gómez-Flechoso, Fux, & Martinet 1999, Johnston et al. 1999, Helmi & White 2001) have sought to model the Sgr - Milky Way interaction with respect to a modest patchwork of observational constraints. Recently, Majewski et al. (2003a, hereafter "Paper I") have shown that the extensive length of the Sgr tidal tails can be traced by M giant stars visible in the all-sky view of the system provided by the 2MASS database. Spectroscopy of Sgr candidate stars has allowed determination of radial velocities throughout the trailing tail (Majewski et al. 2003b, hereafter "Paper II"), and these substantial new constraints can be used to develop more refined models of the Sgr system.

In this contribution, we briefly describe some of the major results of such modeling. A comprehensive description of this new Sgr disruption model can be found in Law, Johnston, & Majewski (2003, hereafter "Paper III").

2.   Modeling the Sgr System

Following previous work by Johnston et al. (1996, 1999) the Milky Way potential is represented numerically by a Miyamoto-Nagai (1975) disk, Hernquist spheroid, and a logarithmic halo. The total mass and radial profile are fixed by requiring that the rotation curve of this model Galaxy be consistent with HI & CO tangent point observations (e.g., Honma & Sofue 1997).

The Sgr dwarf itself is represented by 10^5 self-gravitating particles (representing both the dark and light matter components of the satellite), which are initially distributed according to a Plummer (1911) model. This satellite is evolved through the simulated Galactic potential for five orbital periods using a self-consistent field code (Hernquist & Ostriker 1992). The present-day simulated dwarf is constrained to be located at $(l, b) = (5.6°, −14.2°)$ at a solar distance of $D_{\mathrm{Sgr}} = 24$ kpc (Paper I, Ibata et al. 1995) and have a radial velocity of $v_{\mathrm{LOS,Sgr}} = 171$ km s^{-1} (Ibata et al. 1997). The direction of the dwarf's space velocity vector is determined by requiring that the dwarf orbit in the orbital plane observed in Paper I.

Subject to these requirements, test-particle orbits (i.e. orbits calculated for a test particle with the observed kinematical characteristics of Sgr) and N-body simulations are performed for simulated satellites with a variety of orbital speeds. These simulations can be additionally constrained using the 2MASS M giant distance and radial velocity data presented in Papers I and II. Fig. 1 compares the M giant data (Panels a-b, filled squares) with the model Sgr dwarf whose tidal tails best reproduce the observations (Panels c-d). Note the close agreement between model and observed debris distances and radial velocities along the trailing debris tail $(\Lambda_\odot = 0° - 100°)$[1]. This best-fit model is characterized by a period of 0.75 Gyr with apoGalacticon 52 kpc, periGalacticon 14 kpc, and a present space velocity of $(U, V, W) = (237.2, −43.4, 218.9)$ km s^{-1}.

Although we do not attempt to model the Sgr core in detail, it is nonetheless possible to use the width of the Sgr debris stream to estimate such global characteristics as the bound mass of the dwarf. The simulated dwarf which appears to best fit the width of streams shown in Fig. 1 has a present mass of $M_{\mathrm{Sgr}} = 3 \times 10^8 M_\odot$ and a mass-to-light ratio $M_{\mathrm{Sgr}}/L_{\mathrm{Sgr}} = 21$.

3.   Discussion

As demonstrated in the previous section, the tidal tails of this model provide a good fit to the all-sky view of M giants presented in Papers I and II. It is therefore possible to use this model to determine what range of Milky Way models permit simulated satellites to reproduce observations. Particularly, N-body simulations can be used to constrain the flattening of the Galactic halo (e.g., Ibata et al. 2001). Fitting an orbital plane to leading and trailing M giant debris separately, we determine that the orbital pole of Sgr debris has precessed by $1.7° \pm 2.4°$ over about $300°$ of orbital longitude. Repeating this calculation for N-body simulations in model dark halos with a variety of flattenings, we calculate pole

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[1]We use the orbital longitude coordinate system in the Sgr orbital plane defined in Paper I.
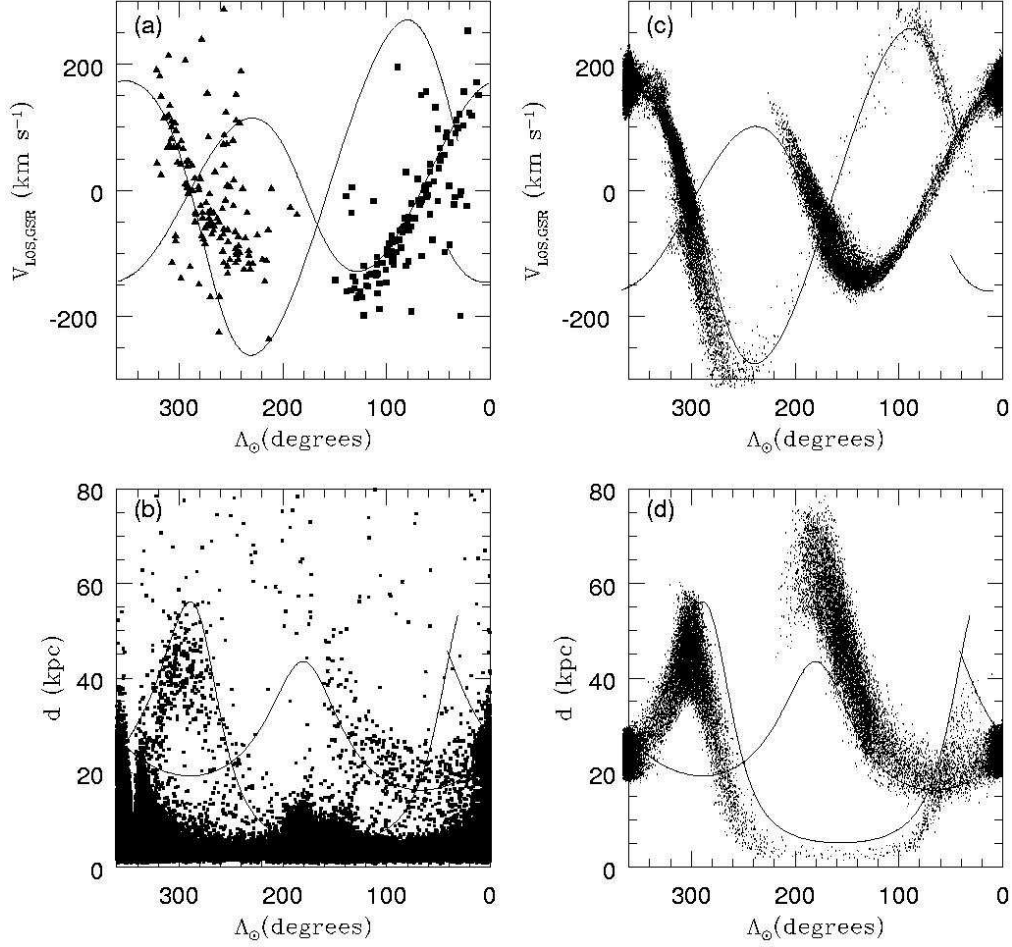
Figure 1. Distance and radial velocity are plotted as function of orbital longitude for M giant data from Papers I & II (Panels (a) - (b), filled squares) and model Sgr debris unbound from the satellite over the last three pericentric passages (Panels (c) - (d)). The solid line in all panels represents the orbit of the model Sgr dwarf core. Filled triangles in panel (a) represent new radial velocity data presented in Paper IV.

precessions of $2.2° \pm 1.6°$, $3.5° \pm 1.7°$, and $5.6° \pm 1.4°$ for flattenings in the halo potential of $q = 1, 0.95$, and 0.90 respectively. It therefore appears likely that the halo of the Milky Way can be described by an almost spherical potential.

Although this model provides a good match to the distances and velocities of trailing Sgr debris given in Papers I and II, it does not fit recent data obtained by Majewski et al. (2003c, hereafter "Paper IV") in the region of the Sgr leading arm. Fig. 1 (Panel a, filled triangles) plots these new data, which has velocities slower than that of the model by up to 200 km s^{-1} in the range $\Lambda_\odot = 300°$ - $200°$. There is no simple modification of the velocity of the model satellite that serves to reproduce this new trend, and this may be an indication of such other effects as dynamical friction. However, simulations suggest that including corrections from Chandrasekhar's formulation of dynamical friction should not have a substantial effect on the observed velocities of leading tidal debris for model satellites with mass $M_{\mathrm{Sgr},0} \leq 10^{10} M_\odot$, and we find that accurately reproducing the observed trend is difficult even for satellites with initial masses greater than this.

This inconsistency and implications of the best-fit model for the size and shape of the Milky Way are discussed at greater length in Paper III.

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